High-Brightness Electron Guns for Linac-Based Light Sources

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ABSTRACT

Most proposed linac-based light sources, such as single-pass free-electron lasers and energy-recovery-linacs, require very high-brightness electron beams in order to achieve their design performance. These beam requirements must be achieved not on an occasional basis, but rather must be met by every bunch produced by the source over extended periods of time. It is widely assumed that the beam source will be a photocathode electron gun; the selection of accelerator technique (e.g., dc or rf) for the gun is more dependent on the application.

The current state of the art of electron beam production is adequate but not ideal for the first generation of linac-based light sources, such as the Linac Coherent Light Source [1] (LCLS) x-ray free-electron laser (X-FEL). For the next generation of linac-based light sources, an order of magnitude reduction in the transverse electron beam emittance is required to significantly reduce the cost of the facility. This is beyond the present state of the art, given the other beam properties that must be maintained. The requirements for current and future linac-based light source beam sources are presented here, along with a review of the present state of the art. A discussion of potential paths towards meeting future needs is presented at the conclusion.

Keywords: FEL injector electron gun emittance

1. INTRODUCTION

The first beam-driven x-ray sources were effectively fixed-target particle accelerators; a moderate-energy electron beam was dumped into a target, thereby producing x-rays. The flux was limited by the available beam energy and power, and by target materials; the resulting x-ray radiation was incoherent and polychromatic.

Synchrotron radiation, the light given off by an electron† beam as its trajectory is deflected by a magnetic field, was originally considered to be a nuisance by the accelerator and particle physics communities, as it limited the electron beam energy obtainable in circular accelerators. Synchrotron radiation sources have since evolved from being effectively parasitic installations on high-energy-physics machines, to dedicated facilities in their own right. They range in size from cyclotrons a few meters across to storage rings a kilometer in circumference, in wavelength from the far-IR to the hard x-ray, and in user community size from individual research groups to thousands of visiting scientists per year.

The so-called "third generation" storage ring sources typically incorporate specialized magnets, known as undulators, to produce a more directional and spectrally narrow x-ray source than can be obtained from the electron beam trajectory-controlling bending magnets. These sources, however, are still mostly incoherent, and for many uses a monochromater is required. Also, due to the dynamics of the particle motion within a storage ring, the electron bunches (and, hence, the x-ray pulses) tend to be fairly long, on the order of a few tens of picoseconds, compared to some other sources of radiation. This limits the ability to perform some types of pump-probe measurements at high time resolution [2].

Partly aside from pulse-duration questions, x-ray users can often be broadly characterized as to how they would improve the characteristics of their x-ray beams: by increasing the raw flux, by increasing the average or peak x-ray

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† Any charged particle will radiate when accelerated; the effect is simply far more apparent in electron machines due to the electron's low mass relative to other elementary particles.

beam brightness (in units of photons per unit area steradian in a narrow bandwidth), or by increasing the coherence of the optical radiation without the need for beamlines hundreds of meters long [3]. Linac-based light sources are least likely to be able to compete on the basis of improving average flux over that from third-generation synchrotron sources, simply because flux scales linearly with average beam current, but in general does *not* scale with parameters for which linear accelerators present a strong advantage vs. storage rings.

A variety of in-construction and proposed future x-ray light sources intend to address the issues of coherence, brightness[‡] enhancement, short-pulse production, or all of the above via use of a linear accelerator rather than an electron storage ring. In a storage ring, the emission of synchrotron radiation will cause an injected electron bunch to "damp" over successive revolutions, finally ending with properties, such as transverse quality and bunch duration, set by the intrinsic properties of the storage ring itself. The beam in a linear accelerator, in contrast, typically does not have the time to damp between the time it is created and the time it is dumped. In particular, for most linear accelerators, the overall quality of the electron beam that can be produced is limited by the source; it is very hard to improve the quality of a beam after it has left the electron gun (although it is often quite easy to make the beam quality worse as it transits the linac). The next generation of linac-based light sources make use of the ability to produce high-quality electron beams, dense in 6-dimensional phase space, to produce bright, short and/or coherent x-ray radiation pulses, for instance via an x-ray free-electron laser (X-FEL). The linac-based light sources may also be broadly categorized according to the type of linear accelerator used: energy-recovering or non-energy recovering. Using an energy-recovery linac allows the possibility of operation at high average beam currents. (Doing so places additional demands on the injector, however, which in general cannot benefit directly from energy-recovery schemes to maintain both high accelerating gradients and high beam currents.) Linac-based light sources in general can also be broadly categorized as sources intended to supplant existing x-ray storage ring user facilities as the brightest incoherent x-ray sources in the world vs. those intended to function as true x-ray lasers. X-FEL facilities are generally anticipated to have relatively long undulators, probably with few (compared to storage ring sources) x-ray beamlines, while storage ring replacement (SRR) facilities will have roughly the same number of user beamlines as existing third-generation synchrotron sources. Hybrid facilities are also possible, with a single linac providing beam to both X-FEL and SRR branches.

In general terms, we will consider only sources using undulator magnets to produce x-ray radiation. Thompson backscatter sources, which generate x-rays by scattering a laser beam from a moderate-energy electron beam, are interesting alternate sources of x-rays; however, they will not be discussed further. Likewise, radiation produced in magnetic elements other than undulators will be ignored for the most part.

There has also been interest of late in designing extremely high-average-power free-electron lasers (FELs) to operate in the mid-IR region; the requirements on the injectors for this type of light source are somewhat different from those operating in the x-ray region and will not be discussed here.

2. X-RAY LIGHT SOURCE CONSIDERATIONS

2.1. General considerations

There are a number of preliminaries to be covered before discussing injector requirements. Since the desired x-ray beam properties, and the accelerator parameters required to obtain them, drive the requirements for the electron gun, those are covered first. The desired characteristics for the injector will be derived separately for X-FEL and SRR light sources.

2.1.1. Undulator radiation

Undulators (also sometimes referred to as wigglers) are specialized magnets used to generate a periodically varying magnetic field transverse to the direction of travel of the electron beam. The electron beam trajectory undulates (or wiggles) as it passes through the device, as shown in Fig. 1. In broad terms, the radiation wavelengths generated in an

[‡] Unless otherwise stated, "brightness" should be taken to refer to x-ray beam brightness, rather than to electron beam brightness.

undulator will be a function of the electron beam energy, magnetic field strength, and the periodicity of the magnetic field.

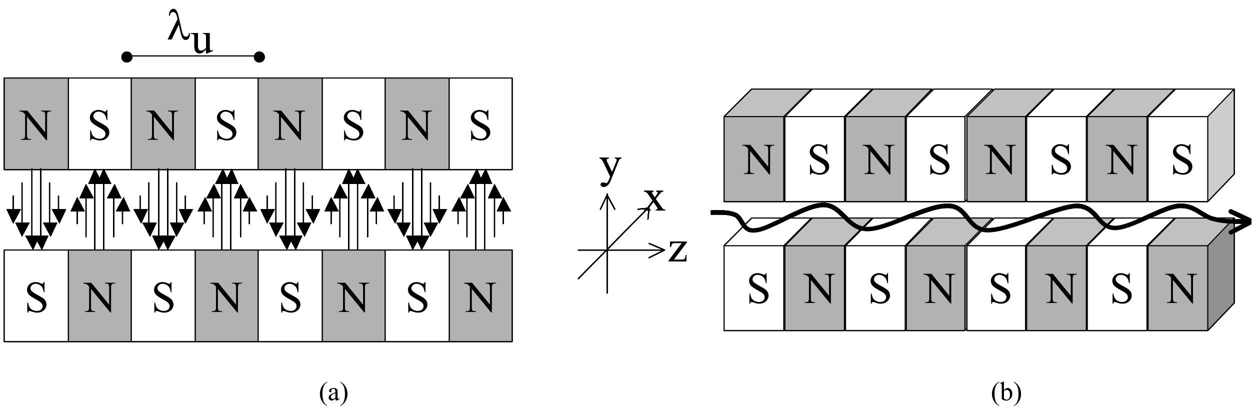

Fig. 1. Field inside an undulator magnet (a) and the corresponding electron beam trajectory (b). The undulator magnet period is λ_u. Note that the magnetic field is in the y direction; the corresponding trajectory oscillation is in the x direction.

There are several ways of calculating the radiation spectrum and pattern produced by an undulator magnet. For instance, the system can be modeled as a dipole source, with a relativistic Doppler shift on the frequency. The longer the undulator magnet and the greater the number of periods (within limits) the narrower the spectrum and radiation pattern will be. Also, the smaller the source size (i.e., the electron beam), the brighter the radiation beam will be.

The wavelength of radiation generated in an undulator is given by

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right), \tag{1}$$

where λ is the wavelength generated, λ_u is the undulator period (defined above), γ is the Lorentz factor of the beam, and θ is the observation angle relative to the axis of the beam. K is known as the undulator parameter and is defined as

$$K = {}^{e B_o \lambda_u}\!\big/_{2\pi m_e c}, \tag{2}$$

where B_o is the peak transverse field along the undulator axis, e is the fundamental electron charge, m_e is the electron mass, and c is the speed of light. K thus represents a normalized undulator field strength. The angular width of the central radiation cone, emitted from a single electron, is given by

$$\theta_{cen} = \frac{\sqrt{1 + \frac{K^2}{2}}}{\gamma\sqrt{N}}, \tag{3}$$

where N is the number of undulator periods. The spectral bandwidth is simply N^{-1}, while the spectral brightness

$$B_{\Delta\omega/\omega} \propto \frac{\gamma^2 N^2 I}{\sigma_x \sigma_y \sqrt{\left(1 + \frac{\sigma'^2_x}{\theta^2_{cen}}\right)\left(1 + \frac{\sigma'^2_y}{\theta^2_{cen}}\right)}}, \tag{4}$$

where $\sigma_{x(y)}$ is the beam horizontal (vertical) spot size, $\sigma'_{x(y)}$ is the corresponding horizontal (vertical) beam divergence, and I is the beam current.

Equation (1) is for a single particle; a real beam includes multiple particles at differing beam energies and trajectories, leading to a broadening of the radiation cone and a blurring of wavelength vs. observation angle. Energy spreads can, given other parameters of the accelerator, be translated into spot size and divergence increases, therefore larger energy spreads can lead to a decrease in brightness as in Eqn. (4).

2.1.2. Electron beam properties

The transverse quality of an electron beam is often specified by the normalized emittance, defined as

$$\varepsilon_{n,u} = \gamma\sqrt{\langle u^2\rangle\langle u'^2\rangle - \langle uu'\rangle^2}\ , \tag{5}$$

where u can indicate either x or y. (This definition assumes that $\gamma >> 1$). Thus the emittance "looks" very much like the product of the electron beam spot size at a waist times the far-field beam divergence, given a small correlation term; the smaller the emittance, the smaller the spot size that can be obtained, or the longer the distance over which the beam can maintain a given minimum spot size. The normalization to the Lorentz factor is done to allow direct comparisons between beam properties at various parts of a linear accelerator. The *un*normalized emittance will decrease as the beam energy is increased and Lorentz contraction reduces the beam divergence angle; the normalized emittance remains constant with acceleration (assuming no corruption of the transverse phase space).

The envelope of a beam, as it transits an accelerator, is described in a normalized fashion via the beta function,

$$\beta_{x(y)} = \frac{\gamma\,\sigma^2_{x(y)}}{\varepsilon_{n,x(y)}} \text{ or } \sigma_{x(y)} = \sqrt{\beta_{x(y)}\frac{\varepsilon_{n,x(y)}}{\gamma}}\ , \tag{6}$$

where $\sigma_{x(y)}$ is the horizontal (vertical) beam size at a particular location along the accelerator.

Although one can play several tricks to improve the brightness of a photon beam generated by an undulator [4], in general one cannot obtain higher spectral brightness by arbitrarily focusing the beam to smaller and smaller spot sizes; the beam will simply diverge more rapidly, thereby largely eliminating the hoped-for gains. The main route towards improving the spectral brightness is improvement of the beam quality and, for peak brightness, also increasing the peak current.

2.2. FEL-specific considerations

Since electrons cannot travel at the speed of light, and since, due to the undulator field, the electron bunch will take a longer path through an undulator than a photon would, electrons in an undulator are always slipping behind the photons they emit. Equation (1), with $\theta = 0$, defines the condition for an electron to "slip" exactly one optical period back per undulator period. Given the presence of an existing optical field in the cavity and the transverse motion of the electron, this permits an energy exchange between the electron and the optical field; see Fig. 2. Under these conditions, there is a non-zero $\vec{v}_e \cdot \vec{E}$, allowing for an energy exchange between the electron and optical field.

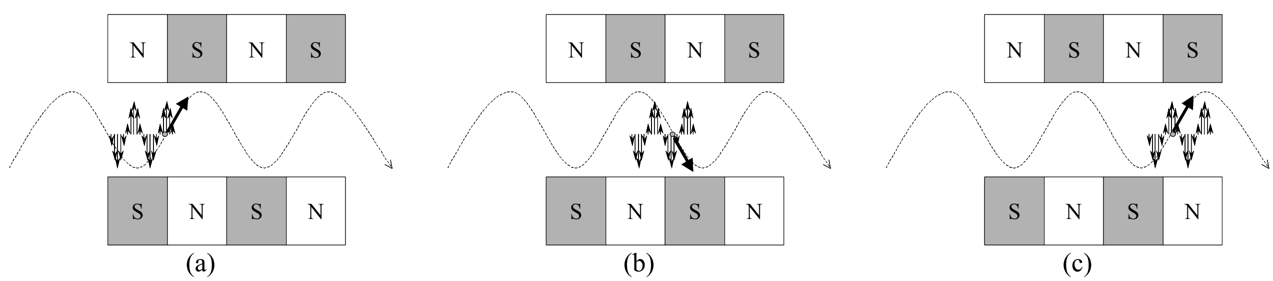

Fig. 2. Beam position (dot and arrow along dashed trajectory line) and optical field (vertical arrows indicating field strength) as a function of position down the undulator: (a) $z=z_0$, (b) $z=z_0+\lambda_u/2$, (c) $z=z_0+\lambda_u$. The trajectory and optical field are shown rotated relative to the undulator magnet for clarity.

In most FELs, gain is provided via an external feedback mechanism; the undulator is placed within a resonant cavity (incorporating a feedback mechanism, i.e., mirrors or Bragg reflectors) used to recirculate the undulator radiation, and multiple electron bunches are sent through the undulator at integer multiples of the cavity round-trip time. The light from one bunch then interacts with subsequent bunches, resulting in a net amplification of the optical field at the resonance wavelength. The net gain per pass is proportional to the mirror losses and electron beam peak current and transverse quality; the higher the peak current, the lower the beam energy spread, and the lower the emittance, in general, the higher the optical gain per transit. The process saturates when the electron beam loses enough energy to the optical field such that it falls out of synchronism with the optical field. The resulting light is monochromatic and coherent, i.e., laser-like. FELs can generally be designed to operate at arbitrary wavelengths, subject to available accelerator and undulator technology. It is also not uncommon for a single FEL to be able to tune over a factor of two in wavelength. For most applications in the visible and near-visible spectrum, however, FELs generally cannot compete with conventional laser sources on the basis of size, cost, or operating complexity. One serious obstacle to building FELs in the VUV and shorter wavelength regions is the difficulty in obtaining suitable mirrors.

Single-pass free-electron lasers are of interest when either suitable mirrors are difficult to obtain or generating a bunch train is impractical. If the electron beam quality is high enough, the FEL interaction described above can take place in a single transit down the undulator, with a single bunch amplifying its own synchrotron radiation to saturation. The process is known as self-amplified spontaneous emission, or SASE, and has been demonstrated at various wavelengths from the microwave [5] to saturation in the visible [6] and UV [6,7]. There are variations on the SASE process, such as high-gain harmonic generation (HGHG) [8], and various seeding schemes intended to provide improved performance in terms of output linewidth and power stability or to reduce the electron beam quality requirements somewhat; but all rely, at some level, on the fundamental internal interaction of a single bunch with its own synchrotron light to generate coherent radiation without the need for external feedback. A critical parameter of a SASE-FEL system is the gain length, or the length of undulator over which the radiation power is increased by *e*. Most first-generation SASE-FEL designs require about ten power gain lengths to come to saturation.

The Pierce parameter, ρ, relates various beam parameters to the gain length of the SASE FEL, with the gain length being inversely proportional to the Pierce parameter. A larger Pierce parameter, therefore, leads to a shorter gain length and a more compact device. The Pierce parameter is defined as

$$\rho = \sqrt[3]{\frac{I_p}{I_A}\left(\frac{\lambda_u K f_b}{2\sqrt{2}\pi\sigma_x}\right)^2\left(\frac{1}{2\gamma}\right)^3} = \sqrt[3]{\frac{1}{I_A}\cdot\frac{\lambda_u^2 K^2 f_b^2}{64\pi^2\beta_x}\cdot\frac{I_p}{\gamma^2\varepsilon_{n,x}}} \tag{7}$$

[using Eqn. (6)], where I_p is the peak beam current, I_A = 17.045 kA (the Alfven current), β_x is the average beta function inside the undulator, and f_b is a gain reduction factor based on the type of undulator chosen (planar or helical, for instance). Thus, all other things being equal, higher peak currents and lower transverse emittances reduce the gain length, resulting in an overall more compact (and less expensive) SASE FEL. Put another way, the higher the beam phase-space density, the stronger the interaction with the beam's own spontaneous emission and the faster the radiation power can grow coherently. According to Eqn. (7), lower beam energies also help to increase the Pierce parameter, but to a certain extent the energy is set by a combination of the desired wavelength (see Eqn. (1)) and one's ability to construct undulators. Undulator periods smaller than 1 cm become problematic for a number of reasons; the K parameter, for instance, falls due to both smaller undulator periods and an on-axis field that decreases along with the undulator period [9].

3. PERFORMANCE TARGET CALCULATIONS

The primary advantages of a linac-based light source over a storage ring, on a single-bunch-to-single-bunch basis, are the possibilities of lower emittance and shorter-duration bunches (both of which lead to higher peak brightness), variable bunch timing, and coherent radiation generation. The first three possibilities are aimed, in general, at doing a better job of producing incoherent or quasi-coherent radiation than present-day storage rings and will be discussed mainly in the context of storage-ring replacements. The final possibility, coherence, instead looks to a more fundamental change to the x-ray beam properties. When calculating the performance targets, therefore, an energy-recovery linac-based SRR will be assumed for brightness enhancement and bunch timing considerations; for the X-FEL, single-bunch performance will be considered independently of the assumed driver linac type. As a further distinction, when discussing emittances, the whole-beam (or projected) emittance is used for SRRs and the "slice" emittance is used for an X-FEL; the difference arises because the SASE process will selectively "pick out" the regions within the beam with the highest gain.

The parameters of the Advanced Photon Source (APS) x-ray user facility will be used for comparison purposes for non-coherent beams. Due to the beam dynamics and radiation damping in storage rings, stored electron beams tend to form “flat” beams with very large transverse emittance aspect ratios. In the case of the APS standard lattice [10], the horizontal normalized emittance is on the order of 41 μm, while the vertical normalized emittance is on the order of 0.4 μm; the nominal unnormalized emittance is 3 nm in the horizontal plane, with 1% coupling to the vertical plane. The nominal stored beam current is 100 mA. The bunch length is on the order of 20–40 ps rms, depending on the charge per bunch, with a maximum bunch repetition frequency of 352 MHz.

In the interests of setting a target towards which to optimize, the goal will be to increase the peak brightness by a factor of 10^2–10^3 over present APS parameters (that is, high enough that obtaining such an enhancement without a significant upgrade to the hardware would be difficult at best) and to not decrease the flux by more than an order of magnitude.

The goals for the X-FEL light source will be based upon operation in the same wavelength regime as the LCLS, with as low a beam energy as reasonable given present-day undulator technology. The injector performance requirements will then be set by the emittance required to reduce the undulator length by approximately the same factor as the linac.

3.1. Higher brightness

Relatively recent results [11] have demonstrated normalized beam emittance on the order of 1 μm for 1-nC charges, from an S-band photoinjector. All other things being equal (in particular ignoring the question of beam current), according to Eqn. (4) this would increase the brightness of the photon beam by a factor of about seven, mainly through the reduction in the horizontal spot size.

In order to reuse many aspects of existing x-ray optics designs, it might be useful to be able to provide “flat” beams to non-FEL users of linac-based light sources. An interesting technique has been proposed to generate such a beam using a magnetized cathode [12] and has been pursued experimentally [13]. Recent results [14] at Fermi National Accelerator Laboratory have reached the normalized electron beam emittances listed above for the APS, with emittance ratios of approximately 50:1 and a “large-plane” normalized emittance of 50 μm. While this would almost reproduce present capabilities, it does not represent an intrinsic performance increase in transverse emittance.

The bunch length in the APS storage ring is on the order of 20–40 ps, depending on the charge per bunch. (One of the advantages of a storage ring is the ability to vary greatly both the “fill pattern” in the ring and the charge per bunch within the fill pattern. For the APS, the charge per bunch can be as high as 18 nC.) A typical bunch length from a high-brightness injector, depending on the particulars, will generally fall in the range of 4–30 ps, usually depending more on the frequency of the linac used than the charge per bunch. Most linac-based light sources assume additional bunch compression; however, assuming a factor of 10–30 bunch length reduction, one might reasonably expect a linac-based light source bunch duration to be on the order of 0.1–3 ps. (One could plan for still more compression; these are intended to be conservative estimates.) Assuming 3 nC per bunch with a 20-ps bunch duration, the peak current for the storage ring would be 150 A; at 18 nC in a 40-ps bunch, the peak current would be 450 A. For the sake of argument, a mean value of 300 A will be used for comparison purposes. Given 1 nC per bunch in an energy-recovery linac (ERL) driving an SRR, the peak currents could be 0.3–3 kA for the linac-based light sources (depending on the assumptions one makes about linac frequency, initial bunch length and compression ratio, etc.) The peak brightness would therefore be enhanced by a factor of up to 10 from peak-current considerations alone. To maintain the same average beam current, with 1-nC bunch charges, the linac-based light source average bunch repetition rate would need to be 100 MHz.

The results of these calculations are summarized in Table 1, assuming both existing (experimentally demonstrated) high-brightness beam source parameters and bunch-compression techniques, and a theoretical improved “low-charge” source design operating at 0.1-μm emittance. The table assumes a nominal 100-mA beam current, with 1 nC per bunch for the existing injector designs (and ignoring the fact that existing high-brightness designs cannot operate yet at the required repetition rate), but 0.1 nC per bunch and 10-mA average beam current for the theoretical improved source design.

Note that the parameters for the “new gun design – round beam” result in almost a factor of two greater brightness than the target value. This is done, in part, to maintain a margin of safety in terms of the desired beam properties; in other words, the “real” emittance can be somewhat worse than the target and still meet the design goals for the facility.

If the users of the new facility do not desire flat beams, then, in principle, there is no immediate need to develop injector technology beyond the present state of the art, as far as single-bunch performance is concerned, to achieve large increases in both average and peak brightness. If flat beams are desired, then new source development is required to increase the peak and average brightnesses in a meaningful fashion. (Many undulator x-ray users at the APS tend to overfill their horizontal apertures and underfill their vertical apertures; round beams would be preferred in these cases, given a choice from the outset [10].)

Table 1. Brightness enhancement factors for several possible beam sources. The net brightness enhancement is normalized to the APS case, at 100-mA average beam current.

	Nominal parameters		Peak brightness enhancement factor		Net brightness enhancement	
Beam Source	Trans. emittance (hor. × vert.)	Peak current (assumed charge)	from ε_n decrease	from I_{peak} increase	peak	average
APS	40 μm × 0.5 μm	300 A	(n/a)	(n/a)	1	1
S-band gun	1 μm × 1 μm	3 kA (1 nC)	$\sqrt{20} \approx 4.5$	10	45	45$^{(1)}$
FNAL flat-beam	50 μm × 1 μm	3 kA (1 nC)	~ 0.75	10	7.5	7.5$^{(1)}$
New gun design	0.1 μm × 0.1 μm	1 kA (0.1 nC)	$\sqrt{400} \cdot \sqrt{5} \approx 45$	3	135	13.5$^{(2)}$

(1) assumes 100 mA beam current (1 nC at 100 MHz)
(2) assumes 10 mA beam current (0.1 nC at 100 MHz)

Going to a lower bunch charge for the "new gun design" accomplishes several things. First, it reduces the space-charge forces acting on the bunch, particularly at low beam energies, leading to easier and less sensitive emittance compensation. Lower charge per bunch also reduces the likelihood of beam quality degradation via coherent synchrotron radiation in the bunch-compression processes [15], and the lower average beam current should allow for an easier energy-recovery linac design as total beam currents will be lower by a factor of ten.

The above discussion concentrates on peak brightness, and for many users of existing x-ray storage rings this is indeed the appropriate figure of merit. Another class of users, for instance crystallographers, are interested primarily in available flux, not brightness per se. In this case, the net flux will be impacted primarily by the average beam current. To even equal the performance of existing sources, then, at a minimum 100-mA beam currents would be required. It seems somewhat apparent that SRR machines will naturally tend towards peak brightness enhancement, as opposed to average flux. Although it is possible that energy-recovery linacs, and the associated injector technologies, will eventually be able to match existing storage rings in terms of flux, it would seem reasonable to concentrate at the present time on those areas in which ERL-based light sources have significant potential advantages over storage rings.

3.2. Bunch timing

There are two aspects to bunch timing considerations. The first is the possible bunch-to-bunch spacing and the other is the duration of a particular bunch.

3.2.1. Bunch-to-bunch timing

The bunch-to-bunch spacing in any rf-driven accelerator, storage ring or linac will be an integer multiple of the rf wavelength used in that accelerator.[§] In a storage ring, the "fill pattern" is often non-uniform, both to accommodate machine issues (such as to leave time for ion clearing) and user requests (e.g., for a given minimum interval between bunches to allow detectors to be read out, etc.) A linac-based light source could in principle have a completely arbitrary bunch delivery sequence; in practice, the sequence will most likely be repetitive and, for an energy-recovery linac, fairly uniform to avoid potentially unpleasant effects in the energy-recovery process. Another aspect of this question relates to average beam current, and thus to average photon beam brightness and flux. For notional bunch charges of 1 nC, an average bunch repetition rate of 100 MHz would be required to maintain a nominal 100-mA beam current. This would

[§] Both linear and circular accelerators often include harmonic rf systems for a variety of reasons; we are referring to the fundamental wavelength of the accelerator in this context.

provide sufficient spacing between the bunches for some users, although present APS "timer" users require 1- to 6.5-MHz repetition rates [10]. A notional injector delivering 0.1 nC per bunch would require a 1-GHz repetition rate to maintain 100-mA average beam currents. This is certainly too high for many existing detector electronics packages, and is liable to remain so for some time. Thus, assuming charge per bunch and emittance per bunch scale roughly together (for the same gun design) there will be a tradeoff in a linac-based light source between peak brightness, and average brightness and flux.

The desire to maintain high average beam currents drives both injector design as well as the desire to use an energy-recovery linac for SRRs. Consider, first, that a 7-GeV electron beam with 100-mA average beam current delivers an average beam power of 700 MW. This is far too great of a beam power to simply dump, both from radiation hazard and simple power-supply considerations. Thus, recirculating the beam to recover its kinetic energy is an almost mandatory feature for an SRR intended to approach the average fluxes of third-generation sources; energy-recovery linac design is a fascinating topic in its own right [16], but one that is beyond the scope of this paper.

The injector, which is most likely not going to be energy-recovering, will need to operate effectively CW to meet the average current requirements. Given beam energies from the injector of around 5 MeV, this implies that the injector itself must deliver beam powers on the order of 50–500 kW. This will pose interesting problems for any injector technology chosen: dc, normal-conducting rf, or superconducting rf.

3.2.2. Bunch-length reduction

One significant challenge being addressed by the storage ring accelerator-physics community is the development of techniques to reduce the duration of bunches in a storage ring. Experimentally, a laser-slicing method at the Advanced Light Source has met with some success [2]. Schemes have also been proposed to use various phase-space manipulations to "rotate" stored beams so as to obtain short bunches [17]. There are various difficulties with these methods, which can include reduced stored-beam lifetimes, relatively small x-ray beam fluxes, applicability to only a few beamlines at most, or the need to use valuable "real estate" around the ring for beam-manipulation systems instead of x-ray beamlines.

A linac-based light source, as indicated above, would be capable of producing considerably shorter bunches almost as a matter of course. The ability to produce very short bunches (in, say the 1 ps–100 fs range or shorter) would dramatically improve the temporal resolution available to x-ray science. Bunches of these durations can be produced relatively easily with existing bunch-compression technology, and these bunch durations could, in fact, be changed almost in real time as the average linac beam current would not be affected. Producing even shorter bunches will become more difficult; however, this is probably not an issue for the injector proper insofar as longitudinal emittance is small enough to allow the desired compression.

3.3. Coherent radiation generation

The first linac-based x-ray light source to start construction, LCLS, is in fact intended to be an x-ray free-electron laser (X-FEL).[**] The standout characteristics of the LCLS X-FEL optical pulse will be the peak power and coherence. (There is an ongoing effort directed towards reducing the LCLS pulse duration, which will probably take place at the expense of average power.) LCLS will be a "first-generation" linac-based coherent light source prototype in the sense that no advanced seeding or harmonic upconversion schemes [8,18] are proposed (at least for first operation) to improve the coherence, spectral linewidth, or other optical pulse parameters beyond that expected from the SASE process [19,20]. Some of these techniques also permit the use of somewhat lower-quality electron beams; however, for the purposes of this paper, we will use the requirements of the basic SASE process as performance benchmarks. Also, the numbers listed for gain lengths, saturation lengths, and other parameters relevant to FEL performance are generated via a quasi-analytic parameterization [21] of the basic SASE-FEL theory, rather than from simulation; therefore, there may be some differences between the numbers stated here and various simulation results. In practice, this formulation has agreed fairly well with SASE-FEL experiments in the visible-to-UV range [22] as well as with simulated LCLS

[**] Technically, the author believes the LCLS should be viewed more as an X-FEL light source prototype, intended to prove the fundamental physics and scaling at x-ray wavelengths. However, as a user-science facility is planned, it will be an operating light source as well as a research machine.

performance. Three parameters of special interest are calculated in this formalism: a diffraction parameter η_d, an emittance gain-reduction parameter η_ε, and an energy spread gain reduction parameter η_γ. They express, roughly and in a proportional sense, how the SASE-FEL gain is reduced due to the light diffracting away from the electron beam in the undulator (based on the beam size in the undulator), the gain reduction due to transverse emittance effects, and gain reduction due to energy spread effects, respectively.

The nominal parameters for the LCLS "High-Energy" case are [23]: Beam energy, 14.35 GeV; normalized emittance, 1.2 μm; rms fractional energy spread, 0.01%; and peak current, 3400 A. For the undulator, the undulator parameter K is 3.7, the undulator period, 3.0 cm, and the average beta function in the undulator, 7.5 m. The resulting optical wavelength is 1.5 Å. The calculated saturation length L_{sat} is on the order of 90 m, $\eta_d = 0.076$, $\eta_\varepsilon = 0.988$, and $\eta_\gamma = 0.086$. Thus, the main limiting factor for the LCLS as designed is the transverse beam emittance. A plot of the emittance vs. gain length and the quantity $\eta_\varepsilon/(\eta_d + \eta_\varepsilon + \eta_\gamma)$ is shown in Fig. 3.

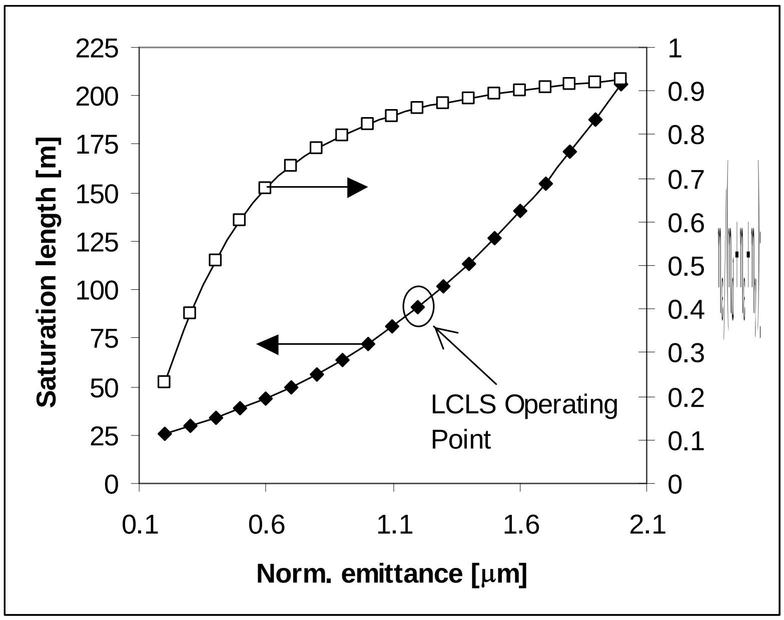

Fig. 3. Plot of saturation length (black dots) and the relative influence of emittance on saturation length (white squares) for LCLS "High-Energy" parameters as a function of emittance.

In this figure, the emittance is changed while all other parameters are held constant. This is not quite fair because, ideally, the beta function in the undulators would be reoptimized for each new emittance, so the saturation length does not drop quite as rapidly as it should. Still, the point is fairly clear: with LCLS, a first-generation linac-based light source, the primary obstacle to reducing the gain length is the transverse beam emittance. At the LCLS operating point, any increase in the transverse emittance will have a strong detrimental effect on the saturation length; if the emittance increases by, say, 10% the saturation length increases by around 10 m. (As a side note, the saturation length for the APS storage ring beam would be around 140 km, assuming an 0.01% rms energy spread.)

Effectively, the emittance is driving the other system parameters, including undulator K and period, as well as beam energy, because existing high-brightness injectors have emittances that are too high. There have been proposals to run LCLS in a low-charge mode of operation so as to take advantage of the reduced emittance this would provide [24]; according to the Pierce parameter, so long as emittance is reduced faster than peak current, the net effect should be beneficial.

Consider instead a hypothetical X-FEL design using an injector that produces a beam with a normalized emittance of 0.1 μm, and assume a beam energy of 7 GeV, the same as in the APS and just over half of that assumed for the LCLS "High-Energy" case. Keeping the undulator period at 3 cm, K can be reduced to 1.3 to generate light at 1.5 Å. If the energy spread and peak currents are relaxed to 0.025% and 1 kA, respectively, and the average beta function in the undulator optimized to about 3 m, the saturation length is reduced to 31 m. Starting with a green-field facility, this would reduce the cost of the linac by a factor of two and the cost of the undulator line by a factor of three, compared to LCLS-nominal design parameters.

Pushing undulators to periods smaller than 1 cm is difficult, in part because obtaining a strong enough magnetic field to keep K at reasonable values (~1–3) becomes difficult [9]. Using an undulator period of 1.25 cm and K=1, a beam energy of about 4 GeV will generate 1.5-Å photons. The same beam parameters as listed above, with an average beta function in the undulator optimized to 2 m, yields a saturation length of ~16 m. (This is a short enough saturation length that significant gain should be observed in just a few meters.) Under this scenario, the linac is under 1/3 the length of the LCLS linac, and the undulator, just over 1/6 as long. Relaxing the bunch compression requirements by reducing the peak current to 500 A or increasing the normalized emittance to 0.15 μm only increases the saturation length to ~ 22 m. At this working point (using 500 A peak current and 0.1 μm normalized emittance), $\eta_d = 0.347$, $\eta_\varepsilon = 0.382$, and $\eta_\gamma = 0.183$, indicating that the overall system parameters are fairly well matched. These calculations are summarized in Table 2.

Table 2. Notional design parameters for three X-FELs operating at ~1.5 Å.

Parameter		LCLS High-Energy	Low-ε design #1	Low-ε design #2
Beam	Energy	14.35 GeV	7 GeV (APS beam energy)	4 GeV (alternate params)
	ε_n	1.2 μm	0.1 μm	0.1 μm (0.15 μm)
	I_{peak}	3400 A	1000 A	500 A (1000 A)
	ΔE/E	0.01 %	0.025 %	0.025 %
Undulator	period	3.0 cm	3.0 cm	1.25 cm
	K	3.7	1.3	1.0
Optimized beta fcn.		7.5 m	3 m	2 m
Saturation length		91 m	31 m	24 m

The ability to drop the beam energy much below 4 GeV and still generate 1.5-Å photons would rely on the development of new undulator technology, capable of generating high K values at very short periods.

4. A TARGET INJECTOR DESIGN

Starting from a somewhat arbitrary desire for at least 10^3 in peak brightness enhancement over existing third-generation synchrotron sources on the one hand, and the desire to use the minimum beam energy to operate and X-FEL at 1.5 Å on the other, we arrive at essentially identical injector single-bunch performance requirements for both SRRs and X-FELs. This is interesting in its own right and points out a factor that should be considered for SRR designs. That is, given normal undulator lengths on the order of 3–10 m, an SRR might fairly easily demonstrate at least some SASE-FEL gain. This is actually a cause for some small concern, as the SASE process tends to increase the beam energy spread on the order of the Pierce parameter, which could lead to brightness degradation for downstream beamlines as well as potential beam loss.

The injector also needs to be capable of producing a beam either at very high peak currents initially (on the order of 500 A–1 kA) or with a longitudinal emittance low enough so as to permit later bunch linearization and compression. This has generally not been of strong concern with existing injector designs; however, as the transverse emittance continues to be reduced, it will become easier to corrupt the transverse emittance.

4.1. Single-bunch considerations

4.1.1. Transverse emittance concerns

The baseline normalized transverse emittance target, based on the values found above, should be on the order of 0.1–0.15 μm to maintain the desired performance for both the SRR and the X-FEL. This provides a reasonable margin of error for both the SRR and the X-FEL light source design parameters as listed above, both in terms of a priori ability to construct the injector and the ability of the injector to operate continuously for extended periods of time (at least 1 week, for instance) without requiring scheduled maintenance.

A candidate design should be capable of demonstrating, in simulation, emittances on the order of 0.07 μm before taking into account other degrading effects such as thermal emittance, cathode nonuniformity, and transverse emittance corruption during bunch-compression processes.

4.1.1.1. Thermal emittance

Except in certain situations [25] that are only beginning to be explored in the context of high-brightness injector design, a photocathode drive laser must provide photons with higher energies than the work function of the cathode material in order to extract electrons. The greater the amount by which the photon energy exceeds the work function, in general, the higher the quantum efficiency, or electrons emitted per incident photon. As the photon energy increases, however, so does the average energy of the emitted electrons. The electrons are generally taken to be emitted at random in energy and solid angle from the surface of the cathode, leading to an intrinsic, or thermal, emittance dependent on the cathode material, drive laser, and laser spot size. The thermal emittance adds in quadrature with emittance arising from space-charge and electromagnetic field effects. Using the rms emittance definition given in Eqn. (5) and assuming that there is no correlation between electron emission location and starting momentum, the thermal emittance can be expressed as

$$\varepsilon_{\mathrm{thermal,rms}} = x_{\mathrm{rms}} \frac{\sqrt{2 m_e E_{\mathrm{kin}}}}{m_e c}, \tag{8}$$

where x_{rms} is the rms laser spot size on the cathode, and E_{kin} is the maximum kinetic energy of the emitted electrons, generally taken to be the laser photon energy minus the work function. The thermal emittance, therefore, can be reduced by minimizing either the laser spot size or the kinetic energy of the emitted electrons. Alternately, one could consider a structured cathode material that would introduce correlations between the emission position and momentum, which would reduce the thermal emittance also. Given the present state of the art, however, the clearest path towards reducing the thermal emittance today consists of reducing the laser spot size.

For most drive laser and photocathode combinations, the range of E_{kin} is on the order of 0.3–2 eV [26]. Therefore, the thermal emittance per rms spot size will range from around 1 μm/mm to almost 3 μm/mm. For existing high-brightness injectors, assuming a uniform-intensity laser spot with a radius of ~1 mm, the thermal emittance can be expected to range from about 0.3–1 μm. Given that thermal emittance contributions to the total emittance should be under 50%, and that total emittances on the order of 0.1 – 0.15 μm are required, rms emission spot sizes on the order of 0.05 mm or less are required. Then, to maintain a notional charge of 1 nC per bunch, the cathode current density would need to increase by about a factor of 20 over existing 1-μm emittance designs; in turn, this implies even stronger gradients at the cathode to help accelerate the beam before space-charge forces can corrupt the emittance irretrievably. Alternately, reducing the bunch charge by a factor of ten while concurrently reducing the spot size will increase the cathode current density far less dramatically and will require, all other things being equal, a smaller increase of gradient at the cathode.

4.1.1.2. Cathode materials and laser profiles

It has been shown [27] that electron beam emission uniformity is critical to the transverse quality of the electron beam. This has two components: the variation in the laser pulse intensity and the variation in the quantum efficiency across the surface of the cathode. To date, there have been few systematic studies of the degradation of the cathode quantum efficiency, especially relative changes across the surface, as a function of time spent in an operational rf gun environment. Known problems for dc guns include ion backstreaming.

Generally speaking, cathode research has been a fairly neglected topic in high-brightness electron gun research. Recent efforts at the Naval Research Laboratory and the University of Maryland have been directed towards correcting this deficiency. In addition, various simulation developers are beginning to work on incorporating more advanced cathode modeling into their codes and are starting to work with cathode materials-science researchers [28].

4.1.2. Longitudinal emittance concerns

The levels of bunch compression required to obtain the desired performance levels are not particularly severe, both by the standards of existing SASE FELs operating in the visible to VUV and by the standards of the LCLS. Given the operating beam energies of the system, the parameters of interest to the next-generation sources, in particular the fractional energy spread for the X-FEL, will be determined in large part by the parameters and operation of the main linac. Indeed, with a final beam energy of 4 GeV, even a 1-MeV absolute energy spread at the gun will be reduced to a relative 0.025% energy spread, modulo various techniques for removing correlations (e.g., with third-harmonic rf systems), wakefield effects, etc.

4.2. Multibunch concerns

The desirable duty factor and pulse repetition rate for an X-FEL system is somewhat debatable, given the projected pulse energies and the very real possibility of having to use a new sample for every pulse. The numbers for SRR-type light sources are more clear, being based on existing facilities designs. As noted above in section 3.2, average beam currents of 10–100 mA would be desired and this, based on detector speeds, will determine the allowed bunch spacing and repetition rates.

4.2.1. Drive laser requirements

We can, however, make some estimates of drive laser requirements without knowledge of the actual repetition rates. The average beam current from a photoinjector can be written as

$$I = f_{rep} E_{pulse} \frac{q_e \lambda}{h c} \eta \, , \tag{9}$$

where I is the time-average beam current, f_{rep} is the (laser or beam) pulse repetition rate, E_{pulse} is the laser energy per pulse, q_e is the electron charge, h is Planck's constant, λ is the laser wavelength, and η is the quantum efficiency in electrons/photon. Since the product $f_{rep}E_{pulse}$ is the average laser power, Eqn. (9) can also be used to determine the approximate average laser power requirements for a given choice of beam current and cathode material. These are summarized in Table 3 for various materials, given "ballpark" parameters for quantum efficiencies.

Table 3. Approximate laser power requirements for various cathode materials. The fundamental laser power requirement assumes 25% conversion efficiency from IR to green and from green to UV, and a fundamental wavelength of 1064 nm.

Cathode Material		Quantum Efficiency	Operating Wavelength	Harmonic laser power needed for:		Fundamental laser power for 100 mA
				10 mA	100 mA	
Metal	Copper	10^{-5}	266 nm	4.6 kW	46 kW	~ 750 kW
	Magnesium	$5 \cdot 10^{-5}$	266 nm	930 W	9.3 kW	~ 150 kW
CsTe		0.5%	266 nm	9.3 W	93 W	~ 1.5 kW
Alkali, NEA		5%	532 nm	0.46 W	4.6 W	~ 20 W

Metal cathodes are immediately disqualified on the basis of both drive-laser power requirements and on the amount of optical power delivered to the cathode. The CsTe-based system is probably reasonable for a 10-mA current system, although extending to 100 mA might be difficult both in terms of building the drive laser and of heat dissipation on the cathode. The alkali and NEA cathodes, or at least cathodes with equivalent quantum efficiencies, appear to be the only real viable candidates for SRR-replacement operation or for high-average-current X-FEL operations. Unfortunately, these cathodes tend to be very sensitive to local vacuum conditions and have short lifetimes.

4.2.2. Electron gun thermal management

DC injectors have the advantage that they do not experience heating, other than through beam current return paths and ion bombardment, when operated at full voltage. On the other hand, rf injectors must take cavity heating into account when planning for high-average-current operation.

The proposed LCLS injector provides an illustration of the magnitude of the problem for normal-conducting designs. Given a design pulse repetition rate of 120 Hz, rf pulse durations on the order of 3 μs, and delivered rf power on the order of 15 MW, the average power delivered to the gun is 5.4 kW.[††] At 1 nC per pulse, the average beam current

[††] The actual LCLS injector design is still undergoing final refinement as of the time of this writing; the rf pulse duration and power levels are taken from the author's experience with this type of injector.

would be only 0.12 μA. Efforts are underway to extend normal-conducting gun operation to very long pulse lengths, both aimed mainly at linear-collider applications [29] and true-CW long-wavelength FEL operation [30]. Previous efforts [31] at duty factors up to 25% (rf operation) have been successful, but further work is clearly required.

For general energy-recovery linac applications intended for very high duty factor to true-CW operation, either dc or superconducting rf (srf) guns would appear to be more reasonable choices simply from a thermal-management perspective. For dc guns, assuming an exit energy of 250 kV and an average beam current of 100 mA implies a 25 kW high-voltage power supply. For srf guns, an average beam kinetic energy of 5 MeV and beam current of 100 mA implies CW rf power requirements (from both a supply and input-coupler standpoint) on the order of 500 kW; this should be attainable with existing technology. A greater challenge for an srf gun would be the heat deposited on the cathode by the drive laser; however, several existing designs under study include cooled cathodes thermally isolated from the body of the gun, so this might not be as large a concern as would first appear.

5. TOWARDS A REALIZABLE DESIGN

At the present time it is unclear whether a single gun design, despite the similarities in single-bunch parameters, will be suitable for both X-FELs and SRRs; it is also unclear whether, in the final analysis, a dc or srf gun would provide greater advantage for the SRR designs.

In any event, fundamental gun designs, be they dc or rf, must improve to the point where 0.05–0.1 μm emittances appear possible with bunch charges of at least 100 pC. On the rf side, some work on large-diameter needle cathodes shows promise [32], although more work is needed to achieve the desired performance (mainly in terms of increasing the bunch charge), and other work is also ongoing. On the dc side, there has been good progress made using large-scale multiparameter optimizations, with recent calculations of 0.7-μm emittance at 0.8 nC and 0.1-μm emittance at 0.08 nC, not including thermal emittance [33].

Good progress is also being made on superconducting rf injector designs. Superconducting gun cavities have been operated at Brookhaven and Rossendorf, and additional design work is ongoing. One of the major challenges involved with srf gun design is the inability to apply external focusing magnetic fields close to the gun cavity. The Rossendorf group, in particular, has made good progress towards using rf focusing at the cathode for beam emittance control. The technology is clearly still evolving.

6. CONCLUSIONS

The injector properties for the SRR light source are driven by the desire to improve the peak brightness by at least a factor of 100 over existing third-generation light sources. The X-FEL injector properties are determined first, by requiring the use of the minimum beam energy possible to replicate LCLS wavelength performance and second, by obtaining approximately the same reduction in undulator length as in beam energy.

The single-bunch parameters required for both next-generation SRR and X-FEL light sources are remarkably similar, and simply obtaining those parameters would appear to be the largest challenge at the moment; an experimental demonstration validating the simulation results in this parameter range is a necessary next step. The challenges include not only the basic "physics" designs of the injectors, but also improving our knowledge of cathode physics, in particular lifetime effects and quantum efficiency degradation (both average and as a function of position on the cathode). Progress is ongoing and appears reasonable in terms of gun physics design, and results from active cathode research programs are eagerly anticipated.

Duty-factor considerations may result in different practical injector designs for SRRs and X-FELs. Due to the high average powers, in general either dc or srf electron guns would appear to be the most promising routes towards high-average-current designs. Good progress has been made on srf gun design at various places, and work continues. In particular, techniques to avoid placing magnetic focusing elements near the gun cavities and to provide for active cathode cooling are progressing well. Remaining challenges here will also include incorporating the physics designs for the ultralow-emittance injectors into an srf-compatible form.

Although much work remains to be done, there appears to be no intrinsic reason why injector design cannot advance to the required levels, both in terms of single-bunch parameters and average beam currents, required for next-generation linac-based light sources. It should be emphasized, however, that additional research is required to attain these goals.

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